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Wavelength Dependence of Noise Figure in InGaAs/InGaAsP Multiple-Quantum-Well Laser Amplifier

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Abstract—Theoretical and experimental results are presented for the wavelength dependence of the noise figure and the single-pass gain in multiquantum well amplifiers. The theoretical model accounts for both conduction band/heavy-hole band and conduction band/light-hole band transitions. The calculations are in good agreement with the experimental results, which indicate that the noise figure has some dependence on the wavelength. A minimum TWA noise figure of 3.9 dB has been measured at 1550 nm for a single-pass gain of 22 dB.

INTRODUCTION

SEMICONDUCTOR optical amplifiers (SOA) based on quantum-wells (QW) have recently been attracting attention, as they offer noise and saturation properties superior to those of conventional bulk SOA's [1], [2]. Previously, a noise figure of 4.6 dB at a gain of 20 dB has been reported for a multiquantum-well (MQW) GaAlAs amplifier [1]. In this letter, measurements of the noise figure for a traveling-

wave amplifier (TWA) at three different wavelengths are presented along with a detailed theoretical assessment of the wavelength dependency of the noise figure. For the 4-well MQW TWA considered here, a noise figure of 3.9 dB at 1550 nm for a single-pass gain of 22 dB is reported.

THEORY

In an optical amplifier the noise is due to spontaneous emission. By considering the differential equations for the average number of photons and the variance of the number of photons passing through a cross-section of the amplifier in a given period of time, the noise figure for a TWA can be evaluated in analogy with [3]:

$$F_{\text{TWA}} = 2 \frac{\Gamma \alpha_e}{\Gamma g - \alpha_{\text{loss}}} \equiv 2 \gamma_{\text{sp}} \frac{g}{(g - (\alpha_a - \alpha_b)) - \alpha_b / \Gamma} \quad (1)$$

where Γ is the confinement factor, α_e the rate of stimulated emission of photons into the considered mode divided by the group velocity of light, g the gain, and $\gamma_{\text{sp}} \equiv \alpha_e / g$ the population inversion parameter. The internal loss is given by $\alpha_{\text{loss}} = \Gamma \alpha_a + (1 - \Gamma) \alpha_b$ where α_a is the loss in the active layers and α_b the loss in the barrier and cladding layers.

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To calculate the gain in (1) the $k \cdot p$ approximation [4] has been used, taking into account both the conduction band/heavy-hole band ($c - hh$) and the conduction band/light-hole band ($c - lh$) transitions. The band structure is assumed to be parabolic, in which case the gain (which is dependent on the polarization of the light) can be expressed as [5], [6]

$$g^{(T)}(E) = \frac{q^2}{\pi \epsilon_0 m_0^2 \hbar c_0 n_R w E} \sum_{\substack{i=c-hh \\ c-lh}} m_{ri} \int_{E_{qi}}^{\infty} |M_i^{(T)}|^2 \cdot (f_c(\epsilon_{ci}) + f_v(\epsilon_{vi}) - 1) \frac{\hbar / \tau}{(\epsilon - E)^2 + (\hbar / \tau)^2} d\epsilon \quad (2)$$

where superscript (T) denotes the polarization (TE or TM), i denotes one of the transitions $c - hh$ or $c - lh$, q is the electron charge, ϵ_0 the vacuum permittivity, m_0 the free mass of the electron, \hbar the reduced Planck's constant, c_0 the speed of light in vacuum, n_R the refractive index, w the width of one well, m_{ri} the relative mass defined as $m_{ri} = m_c m_{vi} / (m_c + m_{vi})$ and E_{qi} the effective bandgap given by $E_{qi} = E_g + E_{cl} + E_{vil}$. E_{cl} and E_{vil} are the first quantized energies of the conduction band electrons and the valence band holes, respectively. $M_i^{(T)}$ is the momentum matrix element between Bloch states in the conduction band and in the valence band. For the $c - hh$ transition the absolute square of the two matrixelements can be expressed as [5] $|M_h^{(TE)}|^2 = (3/4) |M_b|^2 (1 + E_{cl}/\epsilon_{ch})$ and $|M_h^{(TM)}|^2 = (3/2) |M_b|^2 (1 - E_{cl}/\epsilon_{ch})$ where M_b is the bulk momentum matrix-element between two Bloch states [6]. For the $c - lh$ transitions each matrixelement can be expressed as a sum of the matrixelements for the transitions $c - lh1$ and $c - lh2$, and can be evaluated as [7] $|M_l^{(TE)}|^2 = (1/4) |M_b|^2 (5 - 3E_{cl}/\epsilon_{cl})$ and $|M_l^{(TM)}|^2 = (1/2) |M_b|^2 (1 + 3E_{cl}/\epsilon_{cl})$. The energies ϵ_{ci} are given by $\epsilon_{ci} = (m_{ri}/m_c)(\epsilon - E_{qi}) + E_{cl}$. The remaining constants in (2) are the intraband relaxation time τ , the variable of integration ϵ , the Fermi-functions $f_c(\epsilon_{ci})$ and $f_v(\epsilon_{vi})$ and $\epsilon_{vi} = (m_{ri}/m_{vi})(\epsilon - E_{qi}) + E_{vil}$. Equation (2) should normally include a summation over the quantized levels in the well. However, for the InGaAs/InGaAsP system which we are considering, only the first quantized level in the conduction band exists. Thus, the summation is needless as there only is a small probability for transitions between states in the conduction band and valence band with different quantized levels [5]. An expression similar to (2) can be found for $\alpha_e(E)$, the only difference being the Fermi-factor which should read $(f_c(\epsilon_{ci})f_v(\epsilon_{vi}))$ instead of $(f_c(\epsilon_{ci}) + f_v(\epsilon_{vi}) - 1)$.

If we consider only the $c - hh$ transitions, assume that there is no intraband relaxation ($\tau \rightarrow \infty$) and put $\alpha_{\text{loss}} = 0 \text{ cm}^{-1}$ the noise figure can be expressed as $F_{\text{TWA}} = 2(f_c f_v) / (f_c + f_v - 1)$. This expression shows that the smallest noise figure of 3 dB can be obtained if either $f_c = 1$ or $f_v = 1$. This means that a complete inversion ($f_c = f_v = 1$) is unnecessary for a low noise figure. The reason is that although the gain decreases if the inversion is not complete,

so does the spontaneous emission, leaving the noise figure unchanged. The equation also explains the reason for the low noise figure in a QW SOA: because of the staircase-like density of states for the electrons and holes in quantum-well structures and the small effective mass of the electrons in the conduction band, the Fermi-function for the electrons in the conduction band approaches unity rapidly with increasing current, leading to a low noise figure.

MEASUREMENTS AND DISCUSSION

The measurements are carried out on an InGaAs/InGaAsP DCPBH (double-channel planar buried-heterostructure) MQW device, with a bandstructure (conduction and valence band extrema) as shown in Fig. 1. The active region consists of four 80 Å wide InGaAs quantum-wells separated by 130 Å thick InGaAsP barrier layers, lattice matched to InP. The total confinement factor (four wells) is 5%. The length of the cavity is 800 μm; the facets have been antireflection coated, resulting in an average reflectivity of $3 \cdot 10^{-3}$.

The measured values of the single-pass gain, for both TE- and TM-polarized light are shown in Fig. 2, at an injection current of 225 mA. The single-pass gain for TE-polarized light reaches a maximum of 22 dB at a wavelength of 1535 nm. The 1 dB bandwidth of the single-pass gain is in excess of 60 nm. At 1535 nm the gain for the TM-mode is approximately 6 dB lower than for the TE-polarization. The low gain for the TM-polarization is a drawback for the QW SOA, but can be remedied by incorporating strain into the QW-structure [8].

The TWA noise figure can be estimated experimentally by using the formula (which is analogous to (41) in [9]):

$$F_{\text{TWA}} = 2 \frac{P_{\text{meas}}}{\eta} \frac{\lambda^3}{\hbar c_0^2 \Delta \lambda} \frac{1 - R G_s}{(1 - R)(G_s - 1)} \quad (3)$$

where P_{meas} is the measured power of the spontaneous emission for one polarization in a given optical filter bandwidth $\Delta \lambda$, η the total coupling efficiency from the amplifier into the optical power meter, λ the wavelength in vacuum, \hbar Planck's constant, R the modal reflectivity at the appropriate wavelength and G_s the single-pass gain. In (3) it is assumed that the filter bandwidth is several times larger than the mode-spacing in the SOA. (In the measurements a filter bandwidth of 1 nm is used, while the mode-spacing is 0.4 nm.) It should be noted that the total noise figure for a resonant amplifier is given by $F = \eta_i^{-1} X F_{\text{TWA}}$ where η_i is the coupling efficiency and X is the excess noise coefficient given by [10] $X = (1 + R G_s)(G_s - 1)/(1 - R)/G_s$. Fig. 3 shows the measured values of the TWA noise figure for the TE-mode as a function of the wavelength at an injection current of 225 mA. The noise figure varies from 5.1 dB at 1500 nm to 3.9 dB at 1550 nm, indicating a dependence on the wavelength. The uncertainty on the noise figure is estimated to be 0.6 dB. The lowest TWA noise figure of 3.9 dB compares well with a previously reported total noise figure of 4.6 dB [1] considering their excess noise of $X = 0.7$ dB. For comparison, a typical noise figure for a bulk TWA of 5.2 dB [10] has previously been reported.

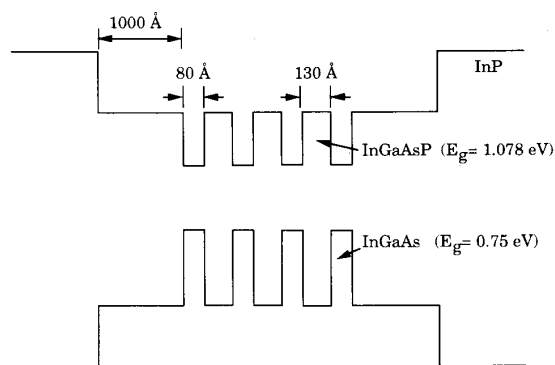


Fig. 1. Energy band diagram (extrema) for the device used in the measurements.

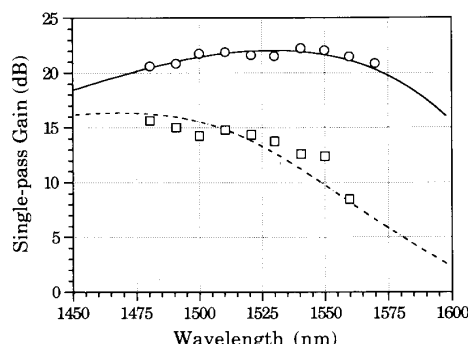


Fig. 2. Measured and calculated results for the single-pass gain versus wavelength at an injection current of 225 mA (TE = \circ , —; TM = \square , ---).

The calculations are performed using the following parameters: $m_c = 0.041 m_0$ for InGaAs (wells), $m_c = 0.064 m_0$ for InGaAsP (barriers), $m_{vh} = 0.44 m_0$ and $m_{vh} = 0.055 m_0$ for both wells and barriers, $E_g = 0.75$ eV for InGaAs, $E_g = 1.078$ eV for InGaAsP and $|M_b|^2 = 4.7 \cdot 10^{-49}$ Jkg. The depth of the conduction band well has been assumed to be 40% of the difference between the bandgaps of InGaAs and InGaAsP. For the internal losses the values $\alpha_a = 215$ cm^{-1} for the active layer and $\alpha_b = 5$ cm^{-1} for the barrier and cladding layers have been used. The bandgap shrinkage due to thermal effects and the presence of free carriers [11] has been taken into account. The Fermi-energies are found from the usual rate-equation for the carriers [12]. An intra-band relaxation time of $\tau = 2.5 \cdot 10^{-14}$ s gives a curvature of the gain spectrum that agrees well with the measurements.

The calculated curves for the single-pass gain for the TE- and the TM-polarization (as indicated in Fig. 2 by the solid and dashed line, respectively) are in good agreement with the experimental results. It is apparent that the gain peak is reached at different wavelengths for the two polarizations. This is due to the fact that the matrix-elements are different for the TE- and the TM-polarization. The calculated noise figure agrees reasonably with the experimental values. However, the wavelength dependence is not reproduced very well. A possible explanation is a wavelength dependency of

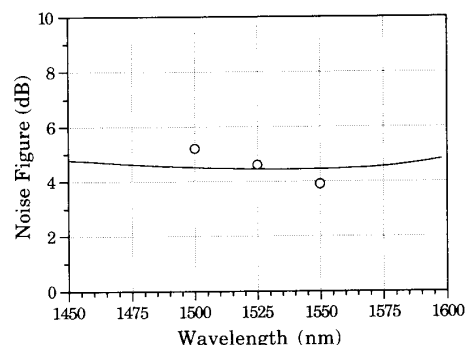


Fig. 3. Measured (\circ) and calculated (—) results for the TWA noise figure (TE-mode) versus wavelength at an injection current of 225 mA.

the internal loss [13]. It is worth noting that the noise figure for a QW SOA is flat over a considerably larger bandwidth than for a bulk SOA [14]; this can be attributed to the staircase-like density of states in a QW. For completeness it should be mentioned that the calculated carrier density is $5.4 \cdot 10^{18}$ cm^{-3} . The inversion is estimated to have a value of approximately $\gamma_{sp} = 1.12$ at the gain peak, which is quite close to the minimum value for the inversion of 1.

CONCLUSION

The wavelength dependence of the noise figure and the single-pass gain for an InGaAs/InGaAsP MQW SOA has been theoretically predicted and is in reasonable agreement with the experimental results. The bandwidth of both the noise figure and the single-pass gain is bigger for a QW SOA than for a bulk SOA. Neglecting the excess noise due to facet reflections, the measured noise figure is 3.9 dB at 1550 nm, increasing to 5.1 dB at 1500 nm, which confirms the low noise properties of QW SOA's.

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+ 21 dBm Erbium Power Amplifier Pumped by a Diode-Pumped Nd:YAG Laser

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Abstract—Efficient energy transfer has been demonstrated in an Er/Yb co-doped phosphorus doped silica fiber for the first time. This has indirectly allowed the use of reliable, high-power AlGaAs diode laser arrays as the semiconductor pump source through the use of a diode-pumped Nd:YAG (DPL) laser operating at 1064 nm. Small signal gains of 42 dB and output powers of 71 mW (+ 18.5 dBm) have been observed with a single DPL. Bidirectional pumping with two DPL's has yielded an output power of 130 mW (+ 21 dBm).

INTRODUCTION

MUCH of the recent discussion regarding the systems deployment of the erbium optical amplifier has focussed on the pump source. 980 and 1480 nm pump sources are the most widely considered options and each have advantages and disadvantages with regards to efficiency, intrinsic noise figure, pump laser power and lifetime. Co-doped fibers are an attractive means of alleviating constraints on the pump source wavelength by using a sensitizer with a broad absorption band. Yb is especially attractive in this regards as it exhibits an intense broad absorption between 800 and 1080 nm, spanning several convenient pump wavelength source options. An efficient amplifier using an $\text{Er}^{3+}/\text{Yb}^{3+}$ co-doped phosphate glass fiber has previously been demonstrated [1]. However, these fibers suffer several drawbacks, including poor mechanical strength, higher intrinsic loss, as well as a thermal and index mismatch when compared to silica fibers.

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Previous experiments with Er/Yb co-doped silica fibers showed inefficient energy transfer [2]. The limiting factor was the relatively long lifetime of the $^4\text{I}_{11/2}$ band of Er, around 3 μs in silica. This allows significant back-transfer to Yb^{3+} with a corresponding loss of inversion. The Yb^{3+} to Er^{3+} energy transfer efficiency is extremely host dependent, with a high phonon energy host being preferred to decrease the intermediate $^4\text{I}_{11/2}$ level lifetime of erbium [3]. For example, we have measured an initial energy transfer efficiency (approaching zero erbium inversion) of only 5% in an Er/Yb germanosilica fiber while the initial transfer efficiency is 90% in a phosphate glass host. We have found that small amounts of phosphorus, when added to silica-based fibers, mimics the spectroscopic environment of the phosphate glass host. Such fibers exhibit greatly improved properties relative to the previously fabricated phosphate glass fibers.

We have chosen to pump on the long-wavelength tail of the Yb^{3+} absorption using a diode-pumped Nd:YAG laser (DPL) operating at 1064 nm. The advantages of the DPL are the use of mature, efficient and high-power AlGaAs diode lasers, the high beam quality and the scalability of this approach with pump array size. Besides the obvious frequency conversion, the DPL is also a brightness converter, allowing up to several hundred milliwatts to be coupled from a single pump source into single-mode fiber. Unlike direct diode excitation, this approach is directly scalable with nondiffraction limited pump array size. Ultrahigh power amplifiers with output powers have been demonstrated in 1.48- μm -pumped erbium amplifiers. These amplifiers, however, require four separate pump sources multiplexed with polarization preserving fiber and bulk beamsplitting cubes. Besides the insertion losses of these devices, they are liable to introduce significant reflections in this high gain amplifier system, both contributing to a degraded noise performance.